Title of the lesson: Aluminium and Al-alloys
Title of the MSc subject: Materials Science
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ALUMINIUM AND Al-ALLOYS

1. INTRODUCTION

In the world of auto manufacturing, aluminium is kind of the new kid on the block. It's being used increasingly in the car world for its lightweight but tough nature. In 2009, aluminium components made up about 9 percent of the weight in most modern vehicles, compared with about 5 percent in 1990 and just 2 percent in 1970.

Aluminium can be used in automotive manufacturing to create body panels for a lighter, more performance-oriented vehicle. Starting with the Acura NSX in the early 1990s, many supercars have been constructed out of aluminium, including the white-hot Audi R8. Wheels are also often made out of aluminium.

In addition, more automakers are switching from traditional iron blocks for engines to aluminium construction. It tends to be not quite as durable as iron, but its lighter weight means a big boost in performance (source: https://auto.howstuffworks.com).

2. PURE ALUMINIUM

The aluminium belongs to the group of the light metals. It is the most important light metal regarding the applications. It has great importance in the Hungarian industry, as its ore, the bauxite is the only metal ore which considerably has occurred in Hungary.
Aluminium is the most abundant metal in the earth's crust and is a constituent of many minerals. However, the material which is highest in aluminium and freest from objectionable impurities is bauxite which, therefore, is practically the only source of the metal under present processes.
Bauxite is the general name given to the hydrated oxides of aluminium. It contains varying amounts of combined water and several impurities of which ferric oxide and silica are usually predominant.
Extraction of the aluminium from the bauxite happens in two steps. In the first step the alumina (Al_2O_3) is extracted by chemical purification. After that the aluminium (of 99…99.7% pure) is produced by electrolysis.
The highest purity aluminium used in the industry has 99.999% of Al. This is extracted by a repeated electrolysis which needs a double amount of energy, therefor these are used in such cases, when the high purity is an important requirement. The high purity aluminium has the best electrical conductivity after the gold, the silver and the copper, therefor it is used as the material of electrical cables (lines). The electrical conductivity decreases with the alloying element concentration linearly or squarely and therefore the high purity aluminium is needed in the electricity.

Aluminium has a very high affinity with oxygen. (Only Beryllium has a higher affinity.) When a new aluminium surface is exposed in the presence of air (or an oxidising agent), it very rapidly acquires a thin, compact, hard, tightly adhering, protective, self healing film of aluminium oxide (about 0,5μ in air). In non-stagnant water, thicker films (of hydrated oxide) are produced. This film is relatively inert chemically. It is on the inactivity of the surface film that the good corrosion resistance of aluminium depends. When the surface film dissolves, dissolution of the metal (corrosion) occurs; when the film suffers localised damage under conditions when self-healing cannot occur, localised corrosion follows. The corrosion resistance fails with several alloying elements (e.g. Cu, Fe), because local galvanic cells evolve on the surface.
The aluminium has a face-centred cubic crystal structure, therefor its plastic ductility is excellent. The elongation is twice of the soft steels. The density is small compared to the steels: 2,7 kg/dm^3. The melting point is low (660 ^{0}C) which is beneficial at the casting technologies. Its heat conductivity is high. At the same time: its strength is low: the yield strength, the tensile strength and the hardness is less than one fourth of the soft steels, therefor (and because of the high price) the aluminium can be competitive between the structure materials, if its strength is improved by alloying.

Table 1: Some properties of commercially pure metals.

	Mg	Al	Ti	Fe
Density / g cm^{-3}	1.74	2.7	4.51	7.87
Modulus / GPa	45	70	120	210
Specific Modulus / GPa cm^3 g^{-1}	25.9	26	26	27
Melting Temperature / °C	650	660	1670	1535
Crystal Structure (300 K)	h.c.p.	c.c.p.	c.p.h.	Cubic–I
Production per annum /tonnes	5×10^5	2×10^7	5×10^5	8×10^8
Energy Cost / MW h tonne^{-1}	??	70	130	15
Relative Cost	7.5	3.7	9	1.0

3. Al-ALLOYS

The alloying elements of the aluminium –regarding their effect - are rated in the following groups:

- For increasing strength: Cu, Mg, Si.
- For improving the corrosion resistance: Mn, Sb.
- For grain refinement: Ti, Cr.
- For increasing the heat resistance: Ni.

- For improving the machinability: Co, Fe, Bi.

The aluminium forms a hard and rigid chemical composition with most of its alloying elements, e.g. Al_2Cu, Al_3Mg_2, Al_3Fe, the following elements are exceptions: Si, Bi, Cd, Zn. The alloying elements can form chemical compositions with each-others, as well. Certain elements can be contaminants in given cases. The best example for that is the Cu which can increase the strength the best, however it has to be avoided in the Al-alloys of corrosion resistance. As contaminant the role of the iron is important because it decreases the corrosion resistance strongly. The oxygen (as the part of the Al-oxide) and the hydrogen (which is adsorbed during casting) always are contaminants.

The aluminium forms a solid solution with most of its alloying elements, and the solution always goes upto a limit. Up to 70 wt% of zinc can dissolve in aluminium (at the melting point of the eutectic composition), followed by magnesium (17.4 wt%), copper (5.7 wt%) and silicon (1.65 wt%). The solubility always decreases with the temperature.

Typical eutectic and a peritectic phase diagrams are illustrated in Fig. 1; these two forms describe the vast majority of phase diagrams for aluminium alloys. In most cases the eutecticum formation is characteristic which can be seen in the left side (e.g. Al-Cu, Al-Mg, Al-Si), however peritectic formation of chemical compounds shown in the right side sometimes can be characteristic, as well (e.g. Al-Cr).

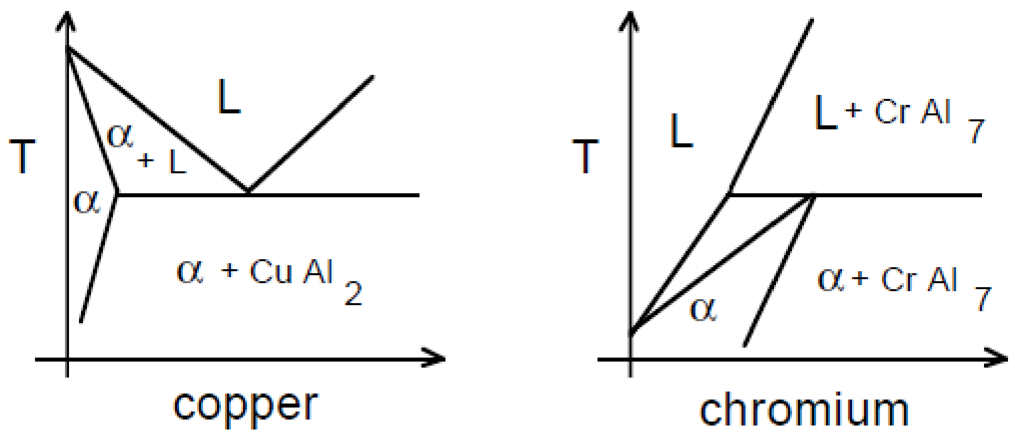


Figure 1: Typical phase diagrams for aluminium alloys, illustrating eutectic and peritectic form.

Since there are no allotropic phase transformations in aluminium, much of the control of microstructure and properties relies on precipitation reactions. The solubility of solute in the matrix (α) is therefore of importance.

4. METALLURGICAL PRINCIPLES OF HEAT TREATMENT OF Al-ALLOYS

The typical heat treatment of the Al-alloys is the **age hardening** alias **precipitation hardening**, whose goal is the increase of the strength of the Al-alloy produced by fine dispersed precipitations. This heat treatment is thus such a method, when disperse precipitations arise in the ductile matrix of the α-solid solution. These precipitations – as it was shown similarly in the lesson of steels – increase the strength because they are obstacles for the movement of the dislocations, that is to say, they put up their effect by the dispersion strengthening mechanism. The first step of the precipitation hardening is the **solutionizing** which is carried out by heating above the solvus temperature for a few hours, and which results a homogenous solid solution. The goal of this solutionizing is the full dissolution of the precipitations, in order to insure the fine precipitations in the later phase of the heat treatment, which results the best favourable strength property. Therefor – in order to ensure the homogenous solid solution – the alloy has to be heated above the solvus line, the temperature of T_1 according to Figure 2, and it is kept on this temperature until the evolution of homogenous solid solution. The temperature of T_1 has to be chosen above the solvus line but below the eutectic temperature.

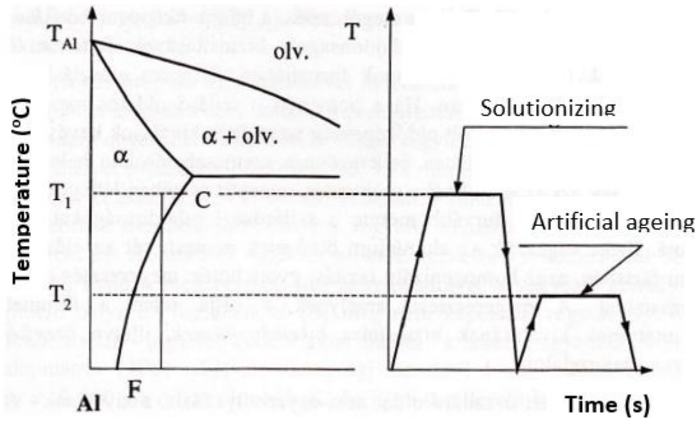


Figure 2: Process of the precipitation hardening

After the solutionizing the alloy is cooled down (e.g. with water) to room-temperature, which is called **quenchin**g. The goal of the quenching is the preventing of the formation of the precipitations in this step of the heat treatment, that is, the goal is creating a supersaturated α-solid solution. This phenomenon is similar to the formation of the martesite (the supersaturated ferrite, the supersaturated α-solid solution) by the hardening heat treatment of the steel. The outcome is however fully other in case of the Al-alloys: in case of the steels, the martensite is the hardest texture element, it has the highest strength because of the stressing effect of the carbon atoms trapped inside the α-solid solution, in case of the Al-alloys however, the strength increase in the supersaturated α-solid solution is small, and this alloy phase is not stable in the most cases, it has not got an own name as martensite in case of the steels.
The second step of the precipitation hardening of the Al-alloys is the **artificial ageing,** which is the true precipitation hardening. The temperature of the artificial ageing is about a quarter of the solutionizing temperature. The criterion of the best strength properties is, that the precipitations has to form in fine dispersed scattering in the matrix. In case of a slow cooling,

the precipitations could grow large and they would be located at the grain boundaries, and these precipitations of larger measure would decrease the strength. Therefor the cooling after the artificial ageing has to be rapid, as well.
As the supersaturated α-solid solution is not an equilibrium phase (it is not stable), the formation of the precipitations (and the resulted strength increase) can go off in given alloys without artificial ageing, over a long time period, at room-temperature, this phenomenon is named by **natural ageing**. The natural ageing in Al-alloys is very slow, it needs months, maybe years, therefor, the artificial ageing is a heat treatment of great importance.

5. CLASSIFICATION OF INDUSTRIAL Al-ALLOYS

A classification of the industrial Al-alloys can be made according to the phase diagram characterizing the Al-alloys.

- The alloys which contain smaller amount of alloying element than the saturated α-solid solution (alloys which have α-solid solution predominantly) are the so called **wrought Al-alloys** (interval signed by I. in Figure 3).
- The alloys which have more amount of alloying element are the so called **casting Al-alloys** (interval signed by II. in Figure 3).

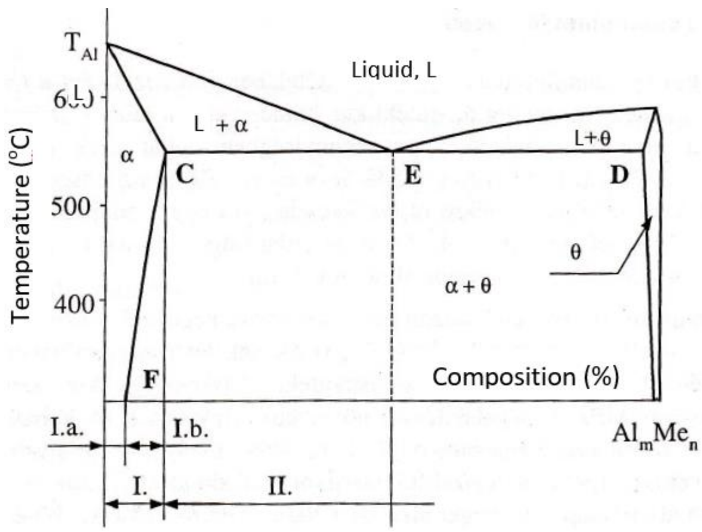


Figure 3: Classification of the Al-alloys

The wrought Al-alloys are divided for two different groups:

- the **non-heat treatable** Al-alloys contain 100% α-solid solution at room temperature (interval signed by I.a. in Figure 3),
- the **heat treatable** Al-alloys are the alloys being at the right side of the solvus, that is, where the vertical line signing a given composition crosses the solvus (interval signed by I.b. in Figure 3).

In the above part of this lesson we could see that the strength of the Al-alloys can be improved by alloying (Cu, Mg, Si) and heat treatment. In case of the wrought Al-alloys the strength can be improved by plastic forming, as well. In order to see the effectiveness of the different strengthening methods, let us see the following example:

- the tensile strength of the primary aluminium (Al 99,5) is about R_m=100Mpa,
- alloying of about 4% Cu, 2% Ni and 1,5% Mg increases the strength to the double value,
- after a heat treatment the strength increases to triple,
- if the alloy was hot forged before the heat treatment, the strength can reach to fourfold, to about R_m=400Mpa.

If all the three strengthening method are applied, a fourfold strength increase can be reached.

Regarding the above strengthening possibilities, the wrought and the casting Al-alloys are divided to separated groups. The structure, the properties, the strengthening possibilities, the technologies and the applications are different in case of the two groups. The wrought Al-alloys generally are sheet metals and they are applied in car body elements. The casting Al-alloys – as their name indicates – generally are casts (ingots) and they are applied in materials of the internal combustion engines. These two groups will be detailed in the following chapters.

6. WROUGHT Al-ALLOYS

The main alloying elements of the wrought Al-alloys are: copper (Cu), magnesium (Mg), silicon (Si) and zinc (Zn), and their amount is less than the composition of the saturated solid solution at the temperature of the eutecticum, that is, the wrought Al-alloys can contain maximum 5% Cu, 10% Mg, 1,5% Si and 4% Zn.

From the group of the **non heat treatable wrought Al-alloys**:

- The Al-Mg alloys of two components, the so called hydronaliums are known about their sea-water resistance. Their relatively small strength can be increased by cold forming (R_m=200-300MPa).
- The Al-Mn alloys can be characterized by excellent corrosion resistance. They are applied in the food industry (e.g. milk transporter containers). They are alloys of small strength: their tensile strength is smaller than 150Mpa without forming.

The **heat treatable wrought Al-alloys** generally have three or more components:

- One of their different types is the so called duraluminium which contain components of Al, Cu and Mg. The tensile strength of these alloys (having about 4% Cu and 2% Mg) can be increased up to 500MPa by precipitation hardening.
- The Al-Cu-Ni alloys can be heat treated to large strength, as well (R_m=400MPa). As they contain Ni, their heat resistance is better than it is in other Al-alloy groups. Both of Al-Cu-Mg and Al-Cu-Ni alloys are of high strength, however their fault is, that the

alloying element of Cu - applied to improve the strength – makes them sensitive against the corrosion.

- The Al-Zn-Mg-Ti weldable alloys are the characteristic examples of the naturally ageable Al-alloys. Figure 4 shows the hardening process after a rapid cooling from 400 ^{o}C.

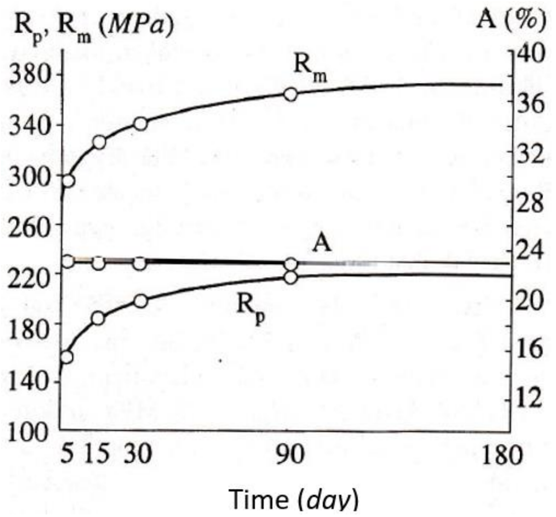


Figure 4: The diagram of the hardening process of Al-Zn-Mg-Ti alloys

The alloy is soft and well formable in the first one-two days after the heating and rapid cooling. It reaches the final strength after 90-180 days. The tensile strength is approximately 400MPa, the yield strength is approximately 200MPa, however its elongation is significant after at the end of the process, it is about 20-22%. It is characteristic, that the heat affected zone is strengthening by natural ageing process, after welding, similarly to the diagram. A disadvantage is that the alloy tends to corrosion because of the component of Zn.

- The Al-Si-Mg alloys contain about 1,5% Si and 1,5% Mg. The strength is moderately high (R_m=400MPa), because they do not contain Cu, at the same time: the corrosion resistance is excellent because of the absence of the Cu.

Applying further additional alloying elements, some properties can be improved further, e.g. an amount of 2% nickel (Ni) raises the heat resistance, an amount of 1-2% manganese (Mn) improves the corrosion resistance, mainly the sea-water resistance.

The chemical composition of the wrought Al-alloys is controlled by the standard of EN 573-3:1995.
The international standard terminology used in the aluminium industry is given in Table 2.

Table 2: Standard terminology, with key alloying elements identified. The exact details can be seen with the numbers that are used to replace the XXX.
* indicates precipitation hardened alloys with strength up to 600 MPa.
** indicates casting alloys.
The silicon–rich casting alloys are often sodium–modified.
Condition T4 includes ageing at ambient temperature.

Alloy Designation	Detail
1XXX	99% pure aluminium
2XXX	Cu containing alloy*
3XXX	Mn containing alloy
4XXX	Si containing alloy**
5XXX	Mg containing alloy
6XXX	Mg and Si containing alloy*
7XXX	Zn containing alloy*
8XXX	Other alloys
Heat Treatment Designation	**Detail**
F	As–fabricated
O	Annealed
H	Strain hardened
T	Heat treated
T4	Solution treated
T6	Solution treated and aged

T6 is a very common heat treatment for aircraft alloys, which after solution treatment are aged for 6–8 h at 150–170 ±C to obtain the required tensile properties. It has recently been discovered that a more complex heat treatment in which the alloys are aged for a shorter time at 150–170 ±C, followed by natural ageing at ambient temperatures, leads to a better combination of tensile and fatigue properties. The natural ageing presumably leads to secondary precipitation on a finer scale.

1XXX These alloys are used in the annealed condition and have a yield strength $\sigma_y \cong 10$MPa, and are used for electrical conductors, chemical equipment, foil and architecture.

3XXX These are the Al–Mn or Al–Mn–Mg alloys with moderate strength ductility and excellent corrosion resistance. The strength, at about $\sigma_y \cong 110$MPa, comes from dispersoids which form in the early stages of solidification. The Mn concentration is restricted to about 1.25 wt% to avoid excessively large primary Al_6Mn particles. Magnesium (0.5 wt%) gives solid solution strengthening and the Al–Mn–Mg alloy is used in the H or O conditions. Beverage can represent the largest single use of aluminium or magnesium. A typical alloy has the chemical composition Al–0.7Mn–0.5Mg wt%.

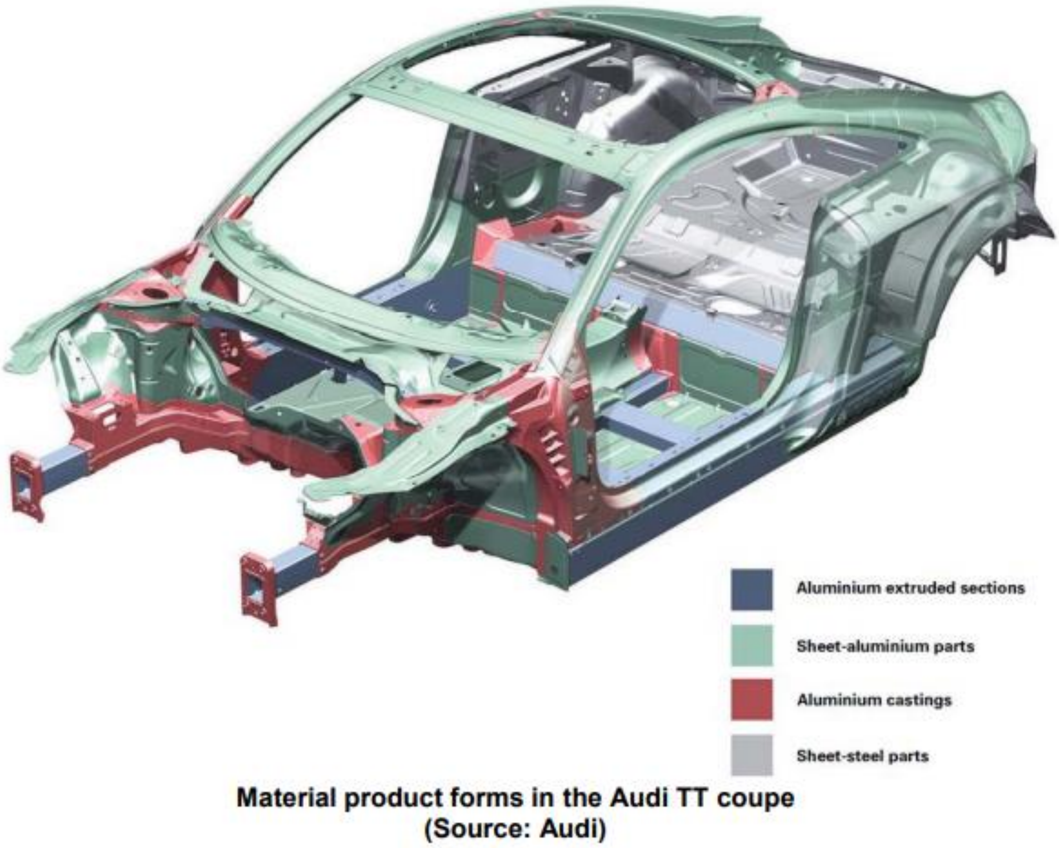
5XXX The magnesium concentration is usually maintained to less than 3–4 wt% in order to avoid Mg_5Al_8. The strength is in the range $\sigma_y \cong$ 40-160MPa with rapid work hardening during deformation. Work hardened aluminium alloys tend to soften with age because the microstructure is not stable even at ambient temperature. Therefore, it is better to excessively work harden and then to anneal to the required strength and stability. The alloys are used to make the bodies of boats or vehicles.

6XXX The strength of the heat treatable Al-Mg-Si alloys belonging to the group of 6000 is supported by age hardening heat treatment. Recently – as cutting-age methods – manufacturing technologies combined with controlled cooling processes have been developed, which result the same high strength (or better strength) as after the age hardening heat treatment detailed above.

7XXX The highest strength can be reached at the Al-Cu alloys in the group of 2000 and at the Al-Zn alloys in the group of 7000. The tensile strength can reach 700 MPa in particular cases. The alloys of these two groups have significant amount of alloying elements. The strength is high however the formability is weaker than in the other groups. The corrosion resistance is not favourable because of the Cu-content. The corrosion resistance has to be ensured by additional technologies. One of them is the cladding: at this technology the sheet metal of high strength is rolled together with an another sheet having excellent corrosion resistance. During the rolling the two sheet are joined together, a good join arises between the sheets.

Application of the wrought Al-alloys in car bodies

Different car body elements of the light cars are prepared by wrought Al-alloys, which significantly contributes to the mass reduction of the cars (compared to the steel car bodies). In Figure 5 the car body of Audi TT coupe is shown. The materials are: sheet, extruded and casting Al-alloys, furthermore sheet steels. In the upper figure the frame structure, in the lower figure the hang-on parts can be seen.



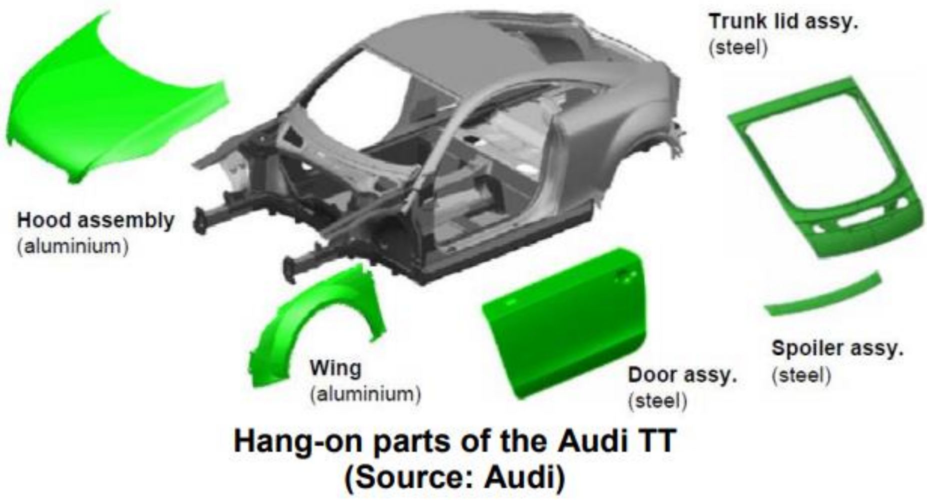


Figure 5: (Source: The Aluminium Automotive Manual, 2013: https://www.european-aluminium.eu/media/1543/1_aam_body-structures.pdf)

In Figure 6 the materials used in the Audi A6 and A7 Sportback car body is shown: the body is built from sheet, extrusion and casting Al-alloys, furthermore, hot and cold formed steels.

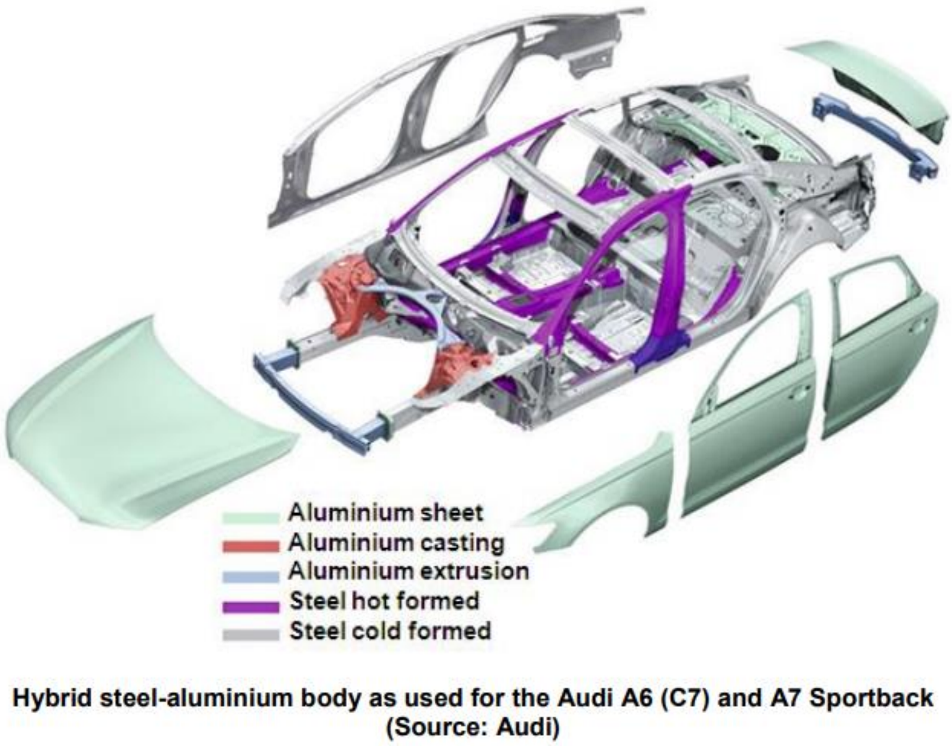


Figure 6 (Source: The Aluminium Automotive Manual, 2013: https://www.european-aluminium.eu/media/1543/1_aam_body-structures.pdf)

7. CASTING ALUMÍNIUM ALLOYS

The casting Al-alloys can be categorized into three groups according to the main alloying element:

- the silicon group (Al-Si alloys),
- the magnesium group (Al-Mg alloys) and
- the copper (Al-Cu alloys) group.

The most outstanding casting alloys belong to the **silicon group**. The characteristic types are the Al-Si and the Al-Si-Mg alloys. The amount of the silicon correspond to the Al-Si eutectic composition (Si=12%) which has a determined melting temperature: T_m=578 ^oC. The shrinkage of the eutectic composition (1-1,15%) is smaller than for other Al-alloys (1,25-1,5%), moreover, it is smaller in case of casting mould (chill-mould) (0,5-0,8%), and therefor they are cut out for casting mould. The strength is better than for the other groups. Al-Si alloys – where the chemical composition deviates from the eutectic composition – are used in different applications, as well, e.g.

- AlSi7Mg alloys are used for additive manufacturing (for laser melting),
- the so called hypereutectic Al-Si alloys (c>12%) often are used as material of the cylinder block in internal combustion engines.

The second cast Al-alloy group, the group of the **Al-Mg cast alloys** is known as hydronalium, however hydronalium is the common name of the Al-Mg sheet form alloys (wrought Al-Mg alloys) and cast alloys. These are alloys predominantly of aluminium, with between 1%-12% of magnesium as the primary alloying ingredient. They also include a secondary addition of manganese, usually between 0.4%-1%. This alloy family is noted for its resistance to seawater corrosion. As such it is used in sheet form for boatbuilding and light shipbuilding. As castings it is used for marine fittings. The reliable strength of some grades is sufficient for aerospace use and so they are used for wetted components of seaplane aircraft, such as floats and propellers, where marine corrosion resistance is also needed. Some variants of the alloy are ductile enough to be drawn into wire. This, combined with their resistance to corrosion by salty sweat, has led to an application for violin strings as an alternative to silver.

The third cast Al-alloy group has the main types of **Al-Cu and Al-Cu-Ni cast alloys**. These are the least disposed to the formation of the shrinkage cavities in case of casting technologies. Good thermal conductivity and certain degree of heat resistance are characteristic for this group. In case of additional alloying ingredients (0.2% Si and 0.3% Mg) they can be cut very good. The Ni ingredient improves the heat resistance. The Al-Cu-Ni cast alloys are used as materials of the cylinder heads and the pistons.

The strength properties of the cast Al-alloys generally are weaker than for wrought Al-alloys. The tensile strength is influenced by the cast technology, as well. It is smaller in case of sand casting, and it is larger in case of sand casting mould. The Al-Cu-Ni and the Al-Mg-Si alloys are heat treatable alloys. Their tensile strength can be increased up 300 MPa by age hardening.

Application of casting Al-alloys in car engines

According to its mass, the engine is the largest part of the car. The primary goal of the developers is the mass reduction at the main parts of the engine: the cylinder blocks and the cylinder heads. Beside this the increase of the power is an another important goal. In such conditions the strength requirements demanded on the parts are increasing continuously. Therefor one of the developer engineers' most important tasks is the economic manufacturing of the engine parts. Because of the above facts, the grey cast iron cylinder blocks and cylinder heads often are changed by Al-alloys.

Engine blocks

As the lesson of the engine block materials is a separated part of this subject, only some data and figure are shown in this lesson, in Figure 7-8.

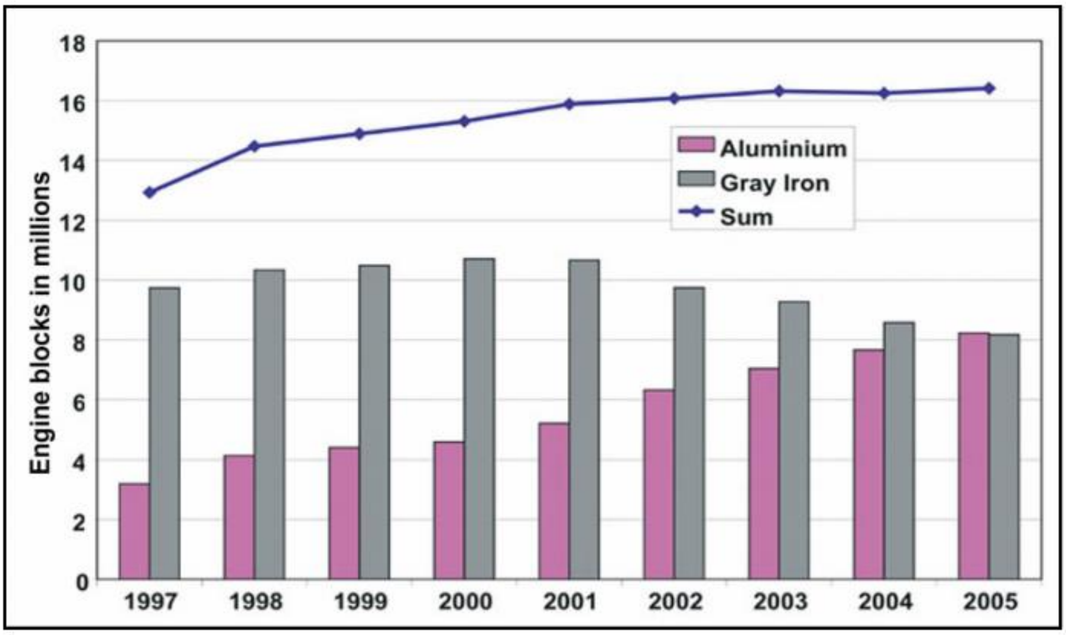


Figure 7: Production numbers of engine blocks in Western Europe (grey iron and aluminium cast alloys) (Source: https://www.european-aluminium.eu/media/1573/aam-applications-power-train-2-engine-blocks.pdf)

Figure 8: Grey cast iron and aluminium HPDC engine blocks (Source: https://www.european-aluminium.eu/media/1573/aam-applications-power-train-2-engine-blocks.pdf)

Cylinder heads

The **alloy selection for cylinder head castings** requires the consideration of various criteria, some of them similar to those used in case of engine blocks. Many cylinder head castings undergo a heat treatment with a subsequent aging. In this case, potential aging effects during operation of the engine over a long period have to be considered too.

The best combinations of strength and ductility are offered by casting alloys with low iron content such as AlSi7Mg0.3 (A356). Therefore, in the past, most cylinder heads were made

from primary aluminium alloys. But also alloys which can be produced using recycled aluminium (i.e. with a slightly increased impurity content) such as AlSi10Mg or AlSi7Mg still provide sufficient ductility. Due to the poor high temperature performance of this type of alloys, new Cu- or Ni-containing alloys have been developed specifically for high performance diesel cylinder heads (e.g. AlSi7MgCu0.5, AlSi9Cu1Mg and AlSi7MgCuFeNi). They provide higher strength at elevated temperatures while maintaining ductility and fatigue performance. Cylinder heads produced with these alloys are usually applied in the T6 condition.
For moderately loaded cylinder heads of gasoline engines, also foundry alloys like AlSi8Cu3 or AlSi6Cu4 (similar to A380.2 and A319, respectively) can be considered. They are widely used for cylinder heads produced in the gravity casting processes. The T4 and T5 conditions are favoured whereas the as-cast (F) condition may cause problems due to insufficient dimensional stability and hardness, the latter being most important for ease of machining.
The commonly and occasionally used alloys for cylinder heads are shown in Table 3.

Table 3 (Source: The Aluminium Automotive Manual, 2013: https://www.european-aluminium.eu/media/ media/1580/aam-applications-power-train-4-cylinder-head.pdf)

Commonly and occasionally used alloys and heat treatments for cylinder heads
(composition of the casting according to EN 1706)

Alloy	Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	Used Tempers
EN-AC-AlSi8Cu3 [1)]	7.5-9.5	0.8	2.0-3.5	0.15-0.65	0.05-0.55	0.35	1.2	0.25	F, T4, T5
EN-AC-AlSi6Cu4 [2)]	5.0-7.0	1.0	3.0-5.0	0.2-0.65	0.55	0.45	2.0	0.25	F, T4, T5
EN-AC-AlSi7Mg0.3	6.5-7.5	0.19	0.05	0.10	0.25-0.45	0.03	0.07	0.08-0.25	T6
EN-AC-AlSi7Mg [3)]	6.8-7.2	0.45	0.15	0.35	0.25-0.65	0.15	0.15	0.05-0.20	T6
AlSi7MgCu0.5 [4)]	6.5-7.5	0.19	0.4-0.6	0.10	0.25-0.45	0.03	0.07	0.08-0.25	T6
EN-AC-AlSi9Mg	9.0-10.0	0.19	0.05	0.10	0.25-0.45	0.03	0.07	0.15	T6
EN-AC-AlSi10Mg(Cu)	9.0-11.0	0.65	0.35	0.55	0.20-0.45	0.15	0.35	0.15	T6

1) A380.2, VDS 226 3) LM25 2) A319, VDS 225 4) not standardized

In practice, the applied alloy composition is optimized depending on the specific cylinder head design and casting conditions. It is important to find a compromise between high temperature strength, ductility and fatigue performance while maintaining reasonable material cost by tolerating certain levels of impurities.
The performance requirements of highly loaded cylinder heads have pushed the suppliers of aluminium castings to develop new process solutions with the aim of increasing the quality of the cast components, minimizing the number of casting defects (porosity, inclusions etc.) and improving the microstructure of the material (dendritic arm spacing). Nevertheless, the current engine development trends leading to higher operating temperatures and increased combustion pressures ask for new alloy developments. Although the performance of the standard Al-Si casting alloys could be significantly improved by the addition of Cu (and other alloying elements) to obtain better resistance at high temperatures (up to 250°C), these improvements might not be enough to meet future engine performance targets. The application of alternative aluminium alloy systems with better high temperature properties (e.g. Al-Cu alloys) will have

to be considered, although their applicability is limited by their poor castability which makes it difficult to manufacture complex castings, like cylinder heads, at high production rates.

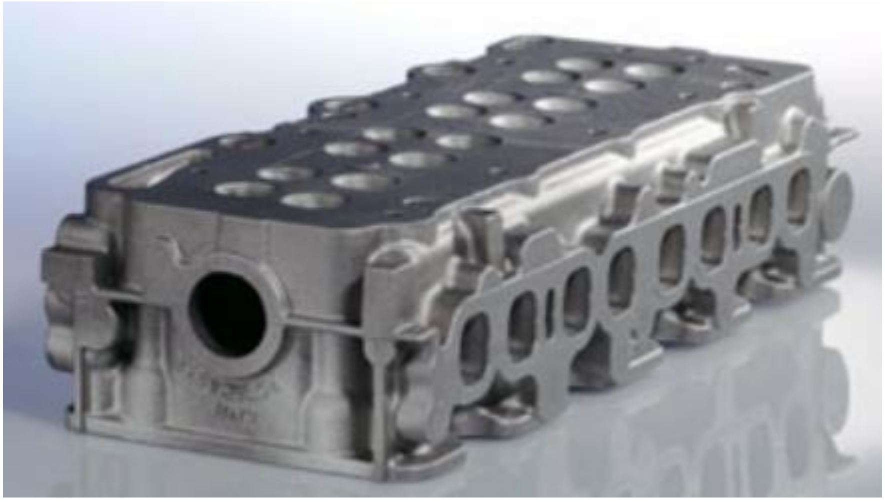


Figure 7: Isuzu diesel 4-cylinder head, alloy EN-AC-AlSi7Mg / T6 temper (Source: The Aluminium Automotive Manual, 2013: https://www.european-aluminium.eu/media/media/1580/aam-applications-power-train-4-cylinder-head.pdf)

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